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Global warming and acidification potential assessment of a collective manure management system for bioenergy production and nitrogen removal in northern Italy

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Abstract:

Collective manure processing facilities to reduce nutrient loads and produce renewable energy are often proposed as feasible solutions in intensive livestock production areas. However, the transferring of effluents from farms to the treatment plant and back to farms, as well as the treatment operations themselves, must be carefully evaluated to assure the environmental sustainability of the solution. This study evaluated the global warming potential (GWP) and acidification potential (AP) of a collective treatment plant for bioenergy production and nitrogen removal as an alternative strategy to conventional on-farm manure management systems. Two manure management scenarios were compared: manure management on individual farms and management by a collective treatment plant. Data were collected at a collective processing plant receiving manure from 21 livestock production units and 660 tonnes day^{-1} of manure treated, and at the individual farms to estimate emissions of CO_2, CH_4, N_2O, NO_x, NH_3 and SO_2. The GWP and AP indicators were calculated to evaluate the potential impact of the two management solutions. The collective solution reduced both GWP (-52%) and AP (-43%) compared to manure management separately by each farm. Further improvement might be obtained in both indicators by introducing mitigation techniques in farm manure storage and manure application to soil.

Keywords: environmental assessment; manure management; collective treatment plant; gaseous emissions; nitrogen removal; anaerobic digestion

1. Introduction

Among agricultural activities, those in the livestock sector have the most critical impact on environmental quality, and manure management causes the main share of pollution [1]. Livestock production makes an important contribution to most economies, and livestock commodities represent the highest value of agricultural production for most countries. In recent decades, the high intensity of livestock production has been accompanied by its dissociation from crop production, because current livestock production techniques substantially rely on imported feed for economic profitability. This approach has generated new challenges related to the treatment and disposal of manure, because increased nutrient concentrations on crop fields and in groundwater and surface water have caused significant environmental problems. The environmental impact of intensive livestock farming is often related to manure management systems and practices that have not implemented updated techniques. Considering livestock intensification, there is a need to develop technology and strategies that address the associated environmental concerns [2,3].

In this context and considering the regulatory constraints (for example the Nitrate Directive of the European Union 91/676/EEC and Industrial Emissions Directive 2010/75/EU), the application of novel techniques of collective manure treatment and management represents a possible solution to improve the sustainability of intensive livestock farms [4].

A manure management system must address the principal local environmental risks and any surplus of nutrients with respect to crop requirements, bringing the cropping system towards a balanced fertilization status.

The design of future manure management systems and the improvement of existing ones should, on one side, focus on maximizing nutrient recycling and controlling manure application rates in order to both reduce the pollution of air, soil and water resources and to improve the human health and safety. On the other side, the systems must be designed minimize the capital and operating costs and the energy requirements [5].

The present concern about global climate change should stimulate practical solutions in areas with nutrient surpluses towards an effective reduction of greenhouse gases (GHGs) by implementing improved manure management systems. At the same time such solutions must also reduce other emissions to air (especially ammonia), leaching of nitrate to water resources, and excessive loading of phosphorus in soils.

Although the environmental impacts related to manure management have been widely investigated [6–8], there is a need for integrated assessment of management solutions. Regulations aiming to minimize the environmental impact of livestock manure are one of the external constraints that farmers must consider. Indeed, when dealing with livestock manures in a whole-farm perspective, the evaluation of cross- and side-effects of regulations based on scientific knowledge still poses significant challenges for farmers [9]. This is often the case for manure processing aimed to reduce the nutrient load and satisfy regulation requirements because such solutions might, as a consequence, increase the emissions to air.

Manure processing facilities can be found both at the individual farm and collective scales. Collective treatment facilities serve several farms and are feasible in areas with intensive livestock production because the concentrated operations facilitate logistic optimization [10]. The operation of these centralized facilities is usually more dependent on road transport than individual plants. The aggregation of farms into a consortium or cooperative for manure treatment benefits from economies of scale. Furthermore, the usual high treatment capacity also facilitates energy production, reducing specific investment and treatment costs, promoting effective operations for the treatment plant and making feasible the introduction of treatment techniques that reduce the effluent nitrogen content. However, the transfer of effluents from farms to the treatment plant and back to farms for utilization must be carefully evaluated to take into account the associated pollutant emissions. Thus, cross effects and emissions to air must be evaluated in the environmental sustainability evaluation of collective manure management/treatment systems.

The main emissions to air from farms are methane (CH_4) produced by ruminal digestion and stored manure, as well as ammonia (NH_3) and carbon dioxide (CO_2) from animal respiration and manure storage. In addition, the spreading of manure on fields results in the volatilization of NH_3 and nitrous oxide (N_2O). Ammonia emissions cause soil and water acidification, together with emissions of NO_x and SO_2. Furthermore, NH_3 emissions contribute to particulate matter formation in the atmosphere. In several European countries, approximately 90% of NH_3 emissions are due to agriculture, 40% of which derive from animal housing and manure storage [11]. Carbon dioxide emissions from agricultural systems are usually negligible because they are overshadowed by emissions from burning fossil fuels. However, CO_2 emissions might be significant from the collective management of manure due to road transport of raw and processed manure. Emissions during transportation include also NO_x and SO_2. The amounts of CH_4 and N_2O emitted to the atmosphere are low compared to CO_2, but their global warming potentials are, respectively, 34 and 298 times higher than that of CO_2 over a time horizon of 100 years [12]. Within the European Union, CH_4 and N_2O emissions from agriculture represents about 10% of the total European GHG emissions and are mainly due to livestock activity and manure (61%) and management of agricultural soil (39%) [13]. The important role played by agriculture and livestock farming in these environmental issues increases the need for reliable models to estimate pollutant emissions from farming activities. These models are used both to highlight the critical points of farming systems and to establish sustainable manure management solutions [9]. In particular, when a new treatment facility is introduced, its effect on greenhouse gases (GHGs) and acidifying emissions also must be evaluated in order to verify its sustainability; such an evaluation might be part of a life cycle assessment (LCA). The magnitude of the potential impact of individual substances can be determined by multiplying the aggregated emission using an equivalency factor for each impact category to which it may potentially contribute. For this purpose, global warming potential (GWP) and acidification potential (AP) indicators are widely used in LCA studies [7,14,15].

The objective of this study was to evaluate the GWP and AP of a collective treatment plant for bioenergy production and nitrogen removal as an alternative strategy to conventional on-farm manure management systems that commonly are used in N-vulnerable areas of the Lombardy region (Italy). To this purpose, a methodology to calculate emissions for two scenarios (manure managed on individual farms or at a collective treatment facility) was defined and implemented. Data were collected through two years of monitoring at both the collective treatment plant and at the individual farms in order to estimate emissions of CO_2, CH_4, N_2O, NO_x, NH_3 and SO_2. The emissions from the two scenarios were then compared both on the basis of individual pollutants and using the GWP and AP indicators. The results were analysed to evaluate the potential environmental impact of the two management solutions.

2. Materials and Methods

2.1. Treatment plant description and data collection

The assessment was conducted in the Province of Bergamo, in Northern Italy, in an intensive livestock production area characterised by a high nitrogen surplus. The area was designated as a nitrate vulnerable zone. Some farms in the area formed a cooperative with the aim to improve manure management and reduce the nitrogen excess while producing electricity. The collective manure treatment plant includes an anaerobic digestion (AD) installation for energy production and biological nitrogen removal (BNR) from digestate (Figure 1).

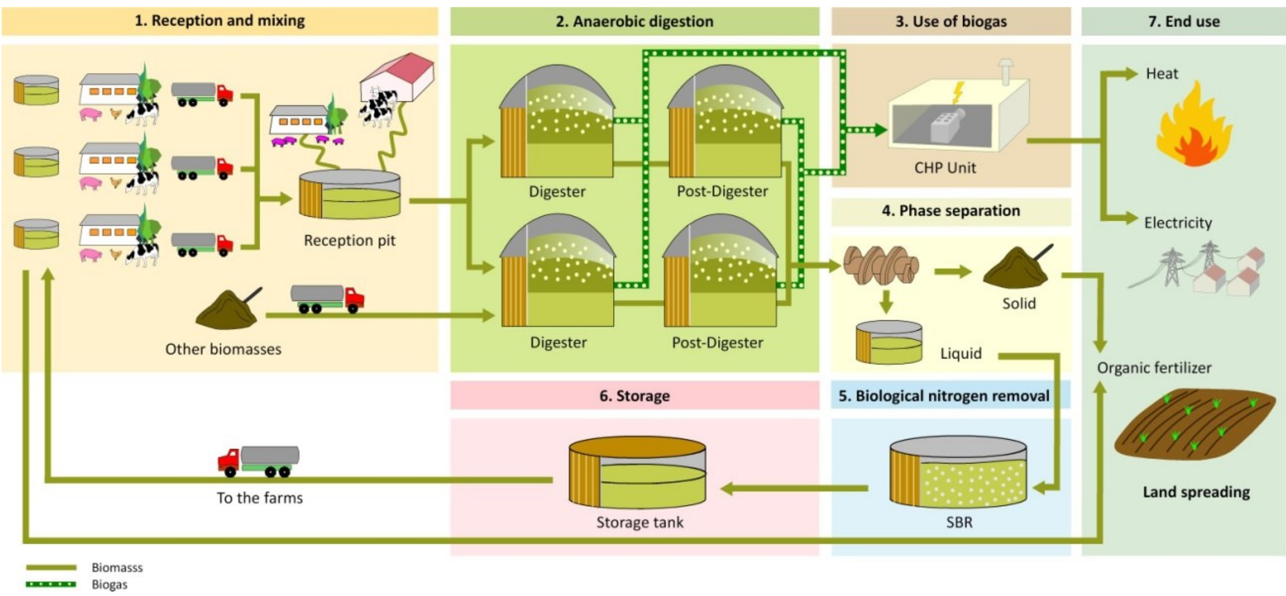

Figure 1. Schematic presentation (flowchart) of the manure management systems for bioenergy production and nitrogen removal considered in the assessment. (CHP = combined heat and power; SBR = sequencing batch reactor).

The collective treatment plant receives manure from 21 livestock production units where pigs, cows and poultry are grown. Table 1 reports the main data about these farms. All farms are located between 0.5 and 16 km from the collective plant. The total daily production of manure for the farms is around 660 tonnes (t). Most of the incoming products consist of manure (slurries and farm yard manure), while the processed liquid effluent after AD and nitrogen removal treatment is the main product transported back to the associated farms.

Table 1. Main characteristics, manure and nitrogen production by the livestock farms considered in the assessment. Live weight has been calculated considering the number of animals and average live weight per head for each category of animal. The amount of manure produced was determined from the recordkeeping of the transportation system. Total nitrogen was calculated using the average concentration of total nitrogen contained in the manure that was periodically sampled in the farms.

Farm	Type of livestock	Live weight (t)	Slurry (t)	Solid Manure (t)	Total N (kg)
1	dairy cows	206	10,398	903	33,589
2	dairy cows	151	8,809	296	30,501
3	dairy cows	184	11,791	-	26,177
4	laying hens	162	-	1,055	12,095
5	dairy cows	100	5,383	255	19,477
6	dairy cows	358	25,445	130	78,356
7	beef cattle	25	795	-	2,339
8	dairy cows	164	10,384	270	27,497
9	fattening pigs	76	4,012	-	12,558
10	fattening pigs	242	6,435	-	27,027
11	dairy cows	349	15,373	416	49,837
12	laying hens	176	-	2,687	30,808
13	beef cattle	810	22,371	2,406	71,924
14	dairy cows	117	4,899	539	20,119
15	dairy buffalo	389	17,435	570	53,944
16	dairy cows	59	2,760	286	9,276
17	dairy cows	231	10,329	1,024	55,154
18	dairy cows & laying hens	440	26,955	1,674	128,893
19	dairy cows	181	8,033	279	23,768
20	dairy cows & beef cattle	662	29,026	1,946	97,530
21	dairy cows	140	4,957	90	16,485

Trucks and slurry tankers transport raw manure from farms to the treatment plant, except for one farm near the treatment plant that is directly connected by means of a pipeline. The first stage involves processing of manure in an AD reactor for energy production. Four digesters and four post-digesters are present, and the digesters are fed with manure and other biomasses (silage). Then, the digested effluent is treated to remove nitrogen and reduce the load of nitrogen and phosphorus on farmers' lands. A solid-liquid separation process produces solid and liquid fractions. The solid fraction is sold to farms in the surroundings of the plant, while the liquid fraction is subjected to BNR through four sequencing batch reactors (SBR) operating in parallel. The final stage consists of storing the effluents in covered tanks and subsequently transporting them back to farms by means of trucks, slurry tankers or pipelines.

Throughout the study, data were collected throughout the production system, and manure characteristics of the 21 livestock farms connected to the treatment plant were determined. In particular, information was gathered on the amount of raw manure transported to the plant and the amount of treated effluent withdrawn from the plant and transported to the farms. Moreover, data were collected about (i) number and type of animals, (ii) storage type and capacity for the treated effluent, (iii) crops and related cultivated surface, and (iv) organisation of manure applications (amounts and scheduling).

The process was monitored for two years and data about the amount of manure treated, the characteristics of the manure in the different stages and energy consumption were determined [16]. The monitoring activity included the transportation of manure to and from the treatment plant in order to assess the energy and emissions associated with the operation.

2.2 Description of the scenarios, system boundaries and stages

To compare the collective system with the individual farm management of manure, two scenarios were considered in the assessment. The baseline scenario (BS) was the system in which every farm manages the manure individually without any treatment, storing the manure produced and applying it to the soil. The collective scenario (CS) was the system in which the manure is transported to the collective processing plant and the treated digestate is transported back to the individual farms, where it is stored and applied to the soil.

In the system boundaries of the BS the following stages were included.

- Manure collection and short-term storage. This stage includes manure removal from livestock and manure storage under slatted floors or in pits collecting liquid manure before it is placed in the main manure storage.
- On-farm manure storage. The slurry and solid manure are stored in open facilities with a capacity of at least 180 days for liquids and 90 days for solid excreta.
- Transport and field application of manure. The operation is performed by slurry tankers that both transport the slurry to the field and then apply the slurry using a splash plate.

In the system boundaries of the collective manure management system the following stages are included.

- Manure collection and on-farm manure short-term storage. A storage capacity of 14 days for each livestock production unit is considered. This storage is functional to the transport system that transports manure to the treatment plant and to intermediate storage.
- Transport to the treatment plant. This stage includes the transport of raw manure by trucks and slurry tankers from the livestock units to the intermediate storage of the collective treatment plant
- Intermediate storage of the raw manure in two continuously-mixed pre-treatment tanks (885 m^3 and 570 m^3).
- Treatment (AD, solid-liquid separation, BNR). This stage encompasses: a) mixture of raw manure with the co-substrates (approximately 10% maize silage, cereals flour, molasses and poultry manure); b) AD; c) solid-liquid separation of digestate; d) BNR; and e) intermediate storage of the treated effluents. AD is carried out in four digesters (mesophilic conditions, 38–40°C) and four post-digesters. The total volume of the digesters is 10930 m^3, while the volume of post-digesters is 12740 m^3. The slurry mixture is pumped to the four digesters, where it is anaerobically digested and then conveyed to the post-digesters. The produced biogas is dehumidified, chilled and fed to two combined heat and power (CHP) units, each capable of producing 1 MW of electric power. CHP output is partially used to heat the digesters and post-digesters. After retention in the post-digesters, the digested slurry is separated through two decanter-centrifuges.. The solid fraction is stored at the plant and sold to nearby farms. In contrast, the liquid fraction is treated through nitrification-denitrification to remove nitrogen in the four SBRs that work in parallel. In each SBR, four phases occur: (i) fill and draw phase (the liquid fraction is pumped in the reactor and the treated slurry conveyed to storages); (ii) mixing

phase; (iii) aerobic phase; and (iv) sedimentation phase. An overall value of 70% has been used for nitrogen removal efficiency based on the data collected during the monitoring activity.

- Storage in the treatment plant. After the BNR unit, the treated effluent is pumped to the intermediate storage at the treatment plant, which consists of three covered storage tanks having a total capacity of 12620 m^3.
- Transport of the end-product to the farms. The treated effluent is moved by trucks and slurry tankers from the collective treatment plant to the individual livestock units that contributed raw manure. As the same truck or slurry tanker is used both for the transport of raw and treated the two transport operations are considered together.
- On-farm manure storage. At farm-level the treated effluent is stored in open tanks for an average period of 100 days.
- Field application. The treated effluent is both transported to the field and applied by slurry tankers. The slurry is applied using a splash plate.

2.3. Emissions assessment

To compare the two scenarios, emissions of CO_2, CH_4, N_2O, NO_x, NH_3 and SO_2 were calculated separately for each stage of manure management in the two systems.

The calculation methodology differed for each stage. When possible, methodologies in previously published guidelines for conducting emission inventories were used, mainly those proposed by the European Environment Agency (EEA) [17] and the Intergovernmental Panel on Climate Change (IPCC) [18]. When available, data directly collected from the farms and the treatment plant were used. Table 2 summarises the methods and tier levels used for the different stages of manure management.

Table 2. Methodology used for the calculation of the emissions for each pollutant (CO_2, CH_4, N_2O, NO_x, NH_3 and SO_2) and for each stage of manure management.

Stage	CO_2	CH_4	N_2O	NO_x	NH_3	SO_2
Farm storage	nd	IPCC, Tier 2	IPCC, Tier 2	EEA, Tier 2	EEA, Tier 2	nd
Transport	IPCC, Tier 2	IPCC, Tier 3	IPCC, Tier 3	EEA ,Tier 2	EEA ,Tier 2	EEA, Tier 1
Intermediate storage	nd	IPCC, Tier 2	IPCC, Tier 2	EEA, Tier 2	EEA, Tier 2	nd
Treatment	Energy mix	IPCC, Tier 2	IPCC, Tier 2	EEA, Tier 2	Monitoring	nd
Transport off-road	IPCC, Tier 2	IPCC, Tier 2	IPCC, Tier 2	EEA ,Tier 2	EEA ,Tier 2	EEA, Tier 1
Land application	nd	nd	IPCC, Tier 2	EEA ,Tier 2	EEA ,Tier 2	nd

nd: not determined

Gas emissions were calculated for both scenarios (BS and CS). All emissions related to the production and management of co-substrates or additional material before entering the plant were not included in the system boundary. Also the environmental impact of the structures and equipment manufacturing was not considered.

To evaluate emissions from storage, data about the pits and tanks used on each farm and in the collective treatment plant were collected. Because the storage period (hydraulic retention time) is limited when the manure is transported to the treatment plant, a duration factor was introduced to avoid overestimation of emissions. Therefore, a linear trend of emissions was considered and the default emission factor (EF) was reduced according to the ratio between the actual storage period and a period of 180 days.

CO_2 emissions from manure storage or treatment were not taken into account because they are considered to be part of the short-term carbon cycle, i.e. resulting from recent CO_2 uptake by crops [19]. For transport and off-road transportation IPCC Tier 2 methodology was used. Emissions were estimated considering fuel consumption and travelled distances that were directly measured during the monitoring period. The energy balance in the treatment plant was determined as the difference between the energy produced and the energy required to run the treatment plant during the monitored period, and was reported on the basis of 346 g CO_2 eq. kWh^{-1} [20].

Fossil fuels consumption of agricultural machinery and their related emissions were included in the analysis as were the emissions from field application of treated effluents.

Methane emissions in both scenarios were calculated using IPCC Tier 2 methodology. For on-farm storage the information was obtained from monitoring data (volume transported to the plant and periodic characterisation of manure). For maximum CH_4 production capacity (B_0), a methane conversion factor (MFC) for each manure management system and default CH_4 density values were used. This method was used also for intermediate storages and final storage. The methane emissions during biogas production were considered to be 1% of the methane produced in the biogas plant. This value was assumed to account for the accidental emissions due to membrane cover permeability [21], leaky gaskets, maintenance operations and flaring or venting of the overproduction [22,23]. For road transportation the IPCC Tier 3 methodology was used. Emissions were estimated from the distance travelled by each vehicle type and road type. For off-road transportation CH_4 emissions were determined using the IPCC Tier 2 methodology and country-specific fuel consumption. For the EF the default value was used.

Nitrous oxide emissions from all manure storage (farm storage, intermediate storage and final storage) occurred in direct and indirect forms, and in both cases the quantities were estimated using the EFs of IPCC Tier 2 methodology, whereas the nitrogen supplied to the manure management system was based on actual monitoring data.

Direct N_2O emissions occur via combined nitrification and denitrification of nitrogen contained in the manure. Nitrification (the oxidation of ammonia nitrogen to nitrate nitrogen) is a necessary prerequisite for the emission of N_2O. Nitrites and nitrates are transformed to N_2O and dinitrogen (N_2) during the naturally occurring process of denitrification, an anaerobic process. Direct N_2O emissions during treatment (in the SBR units) were obtained using the EF for direct N_2O emissions from a manure management system in accordance with IPCC methodology (0.005% of total nitrogen, aerobic treatment with forced aeration systems). Emissions were estimated from total annual amount of nitrogen treated, which was assessed through direct analysis of manure composition during monitoring period. As for CH_4 emissions, road transportation emissions of N_2O were estimated from the distance travelled by vehicle type and road type (IPCC Tier 3), whereas off-road transportation emissions were determined using the IPCC Tier 2 methodology and country-specific fuel consumption. Direct N_2O emissions from land application were calculated using the IPCC Tier 2 methodology. The EF for direct soil emissions was set at 1% of the nitrogen applied to soils or released from soils through activities that result in mineralisation of organic matter in mineral soils.

Indirect emissions result from volatile nitrogen losses that occur primarily in the form of NH_3 and NO_x (nitrogen returned to the soil from volatilisation of manure during management). In addition, nitrogen is also lost through runoff and leaching into soils from manure storage. Thus, a portion of the nitrate that is leached can also be denitrified and result in N_2O emissions [24]. The values of the fraction of livestock nitrogen input that volatilises as NH_3 and NO_x, as well as the values of the fraction of the manure nitrogen lost to leaching and surface runoff, were also based on IPCC guidelines.

The nitric oxide emissions were estimated following the method proposed by EEA for Tier 2. The EFs, as a proportion of total ammoniacal nitrogen (TAN), were specific for each manure type (slurry or solid) and each stage (storage and treatment) of manure management. Transportation emissions were estimated from the distance travelled by vehicle type and road type using EEA Tier 2 methodology. The NO_x emitted during land application was estimated using the EEA 2009 Tier 1 method.

Ammonia emission occurs from all activities in which manure is in contact with air (storage, land application, and storage in tanks without any cover in treatment plants) and from transport activities. Ammonia emissions that occur during manure storage, treatment, transport and land application were estimated using the EEA Tier 2 methodology and a mass flow approach through the manure management systems. The EFs for each stage in manure handling, expressed as a proportion of TAN, were specific for each manure type (slurry or solid). Transport emissions were estimated from the distance travelled by vehicle type and road type (EEA Tier 2 method). Ammonia emissions from treatment operations were considered to be 1.8% of the total nitrogen treated [25]. For the final storage the same EEA Tier 2 methodology was used as for intermediate storage, but the TAN content was calculated according to the transformation in the treatment plant. To evaluate emissions during land application the average conditions, derived from the farm practice observed through recordkeeping on the farms, were used to obtain an average EF. As the EF is expressed as percentage of the TAN content of the manure, the emissions after the treatment considered the nitrogen removed during the treatment process.

Sulphur dioxide emission takes place in all those activities in which manure or end-products are transported. The SO_2 emissions were estimated using the EEA Tier 1 methodology and country-specific fuel consumption, and assuming that all sulphur in the fuel is transformed completely into SO_2.

2.4. GWP and AP calculation

Emissions evaluated for the different stages were utilised to obtain the GWP and AP based on the following equivalency factors:

- 1, 34 and 298, respectively, for CO_2, CH_4 and N_2O to obtain GWP expressed in CO_2 eq. [12].
- 1.6, 0.5 and 1.2, respectively, for NH_3, NO_x and SO_2 to obtain AP expressed in SO_2 eq. [14,19].

3. Results

3.1 Emissions in the baseline scenario

The evaluation of the emissions by management systems in the baseline scenario (BS) related to individual livestock production units are summarised in Table 3.

The AP (440 t SO_2 eq.) mainly (98%) is due to ammonia emissions. Both the NO_x and SO_2 emissions are very limited. NO_x derives mostly from nitrogen transformation after manure application to soil; SO_2 is produced during transportation. Approximately 31% of AP is due to manure collection and storage while the remaining derives from the emissions during manure spreading (Figure 2). The variability of AP among livestock units is high in absolute value reflecting their different sizes and types. However, by referencing the emissions to the live weight of animals, the mean ± standard deviation is 84.2 ± 28.5 kg SO_2 eq. (t of live weight)$^{-1}$. Thus, even on a live weight basis the variability is still high because the emissions are affected by the type of livestock and management system in place (which, in turn, determine the amount of nitrogen produced, size of the manure storage pits and size of storage tanks).

The GWP (22,600 t CO_2 eq.) was mainly contributed by CH_4 (69%) and N_2O (20%). Methane is produced during storage and in very limited quantity during transport, while N_2O is generated in all management stages. The remaining 1% of GWP is due to CO_2 emitted from diesel fuel combustion during manure transport to the field. Figure 3 shows that manure collection and storage account for 84% of the total emissions and the application to soil accounts for only 15%.

As is the case for AP, the variability in GWP among livestock production units is large. When referenced to the live weight of animals, the mean ± standard deviation of GWP is 4.3 ± 2.0 t CO_2 eq. (t of live weight)$^{-1}$. The lower values are related to livestock units with laying hens, where only solid manure is produced and the CH_4 generated represents only 44% of the total GWP. The higher value reflects the high CH_4 production of some dairy cow units with a large number of animals and limited production of solid manure.

3.2 Emissions in the collective treatment scenario

To better compare results for the BS and CS scenarios, the results for the CS scenario are reported for each livestock production unit even though a collective treatment plant was adopted in CS (Table 4).

As in the BS, the AP (253 t SO_2 eq.) in the CS derives mainly (98%) from NH_3 emissions. As shown in Figure 3, approximately 50% of the emissions occur during land application, while the emissions from the treatment plant account for 13% of the total. The remaining AP is contributed by the collection and storage of manure on the farms, both before and after manure processing. The mean ± standard deviation AP referenced to the unit of live animal weight is 48.4 ± 15.7 kg SO_2 eq. (t of live weight)$^{-1}$.

Table 3. Emissions, acidification potential and global warming potential for each livestock production unit in the baseline scenario (manure managed individually on each farm).

Livestock unit	NH_3 (kg year^{-1})	NO_x (kg year^{-1})	SO_2 (kg year^{-1})	SO_2 eq. (kg year^{-1})	CH_4 (kg year^{-1})	CO_2 (kg year^{-1})	N_2O (kg year^{-1})	CO_2 eq. (t year^{-1})
1	9,747	791	0.06	15,991	22,785	11,003	636	975
2	9,888	711	0.03	16,177	25,902	6,453	578	1,059
3	7,876	622	0.06	12,913	25,809	11,489	494	1,036
4	4,368	300	0.00	7,139	1,052	752	153	82
5	6,704	451	0.02	10,952	13,063	4,000	373	559
6	26,703	1,830	0.13	43,640	73,300	24,907	1,489	2,961
7	668	55	0.00	1,096	1,615	567	44	69
8	8,672	644	0.04	14,198	21,005	7,574	523	877
9	4,662	292	0.01	7,604	5,758	2,851	240	270
10	9,725	629	0.02	15,874	13,869	4,567	515	630
11	17,826	1,155	0.08	29,099	30,726	15,384	956	1,345
12	11,126	764	0.01	18,183	2,679	1,900	389	209
13	21,339	1,682	0.09	34,983	34,756	17,572	1,378	1,610
14	6,387	468	0.02	10,454	12,631	3,858	385	548
15	19,287	1,245	0.07	31,481	27,179	12,764	1,033	1,245
16	2,670	218	0.01	4,381	7,022	2,156	177	294
17	17,108	1,288	0.04	28,017	36,704	8,042	1,048	1,568
18	41,756	3,041	0.10	68,330	75,914	20,296	2,290	3,284
19	6,785	562	0.03	11,137	19,214	5,886	448	793
20	29,792	2,283	0.11	48,809	62,350	21,969	1,856	2,695
21	5,728	382	0.02	9,356	11,124	3,574	314	475
Total	268,815	19,415	0.96	439,813	524,455	187,562	15,318	22,58[illegible]

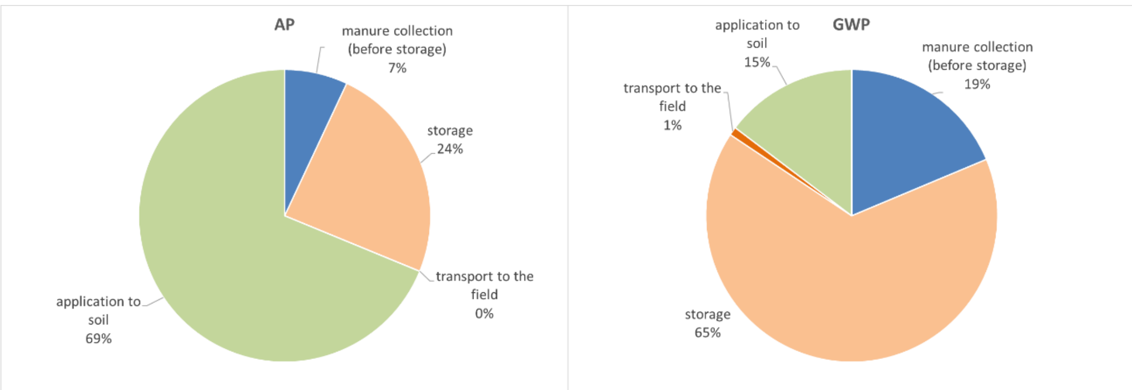

Figure 2. Contribution to acidification potential (AP) and global warming potential (GWP) of the different stages of manure management in the baseline (BS) scenario (manure managed on individual farms).

The GWP indicator for CS is affected by the renewable energy produced, which reduces the total CO_2 eq. emissions. However, the saving does not completely offset the emissions of GHGs in the form of CH_4 and N_2O. Thus, the GWP is still positive (10,721 t CO_2 eq.). Without accounting for the energy produced, the GWP of CS would be 14,969 t CO_2 eq., only 65% of which is due to CH_4 emissions, while 29% is due to N_2O.

The contribution of the different stages of the system to GWP, reported in Figure 4, provides evidence that the emissions during collection of manure and storage on the farms are approximately 60% of the total. Treatment contributes 15% of total GHGs emissions due to the N_2O production during the nitrification-denitrification process.

The GWP, including the offset from energy production, referenced to the animal live weight, is 2.1 ± 0.9 t CO_2 eq. (t of live weight)$^{-1}$.

Table 4. Emissions, acidification potential and global warming potential for each livestock unit of the collective treatment scenario (manure is transported from each farm to a collective treatment system and treated effluent is transported back to the farms).

Livestock unit	NH_3 (kg year^{-1})	NO_x (kg year^{-1})	SO_2 (kg year^{-1})	SO_2 eq. (kg year^{-1})	CH_4 (kg year^{-1})	CO_2 (kg year^{-1})	N_2O (kg year^{-1})	CO_2 e (t year
1	5,908	505	0.17	9,705	13,145	-148,289	603	478
2	5,609	445	0.16	9,198	13,801	-152,399	533	476
3	4,664	416	0.21	7,670	13,136	-133,448	481	456
4	2,595	164	0.03	4,234	846	-67,930	173	12
5	3,740	277	0.07	6,122	7,233	-85,329	341	262
6	14,874	1,129	0.32	24,364	37,578	-430,560	1,377	1,257
7	389	35	0.01	639	838	-11,202	41	30
8	5,047	405	0.09	8,277	11,501	-137,457	497	402
9	2,697	182	0.10	4,406	2,803	-31	217	160
10	5,567	372	0.16	9,093	6,748	-15,371	453	349
11	9,874	718	0.22	16,157	16,816	-183,507	880	650
12	6,610	413	0.04	10,782	2,154	-179,324	439	25
13	12,934	1,130	0.60	21,260	23,135	-265,626	1,311	912
14	3,693	286	0.07	6,052	7,695	-94,058	354	273
15	10,777	828	0.47	17,657	15,313	-155,152	959	651
16	1,619	135	0.02	2,658	4,223	-52,912	167	141
17	9,664	765	0.17	15,845	20,806	-248,511	938	738
18	23,425	1,849	0.70	38,405	40,431	-472,312	2,129	1,537
19	4,033	355	0.11	6,630	10,431	-115,066	424	366
20	17,447	1,428	0.41	28,629	35,990	-416,836	1,734	1,324
21	3,178	237	0.08	5,204	5,843	-62,659	288	222
Total	154,341	12,075	4.22	252,987	290,466	-3,427,979	14,339	10,72

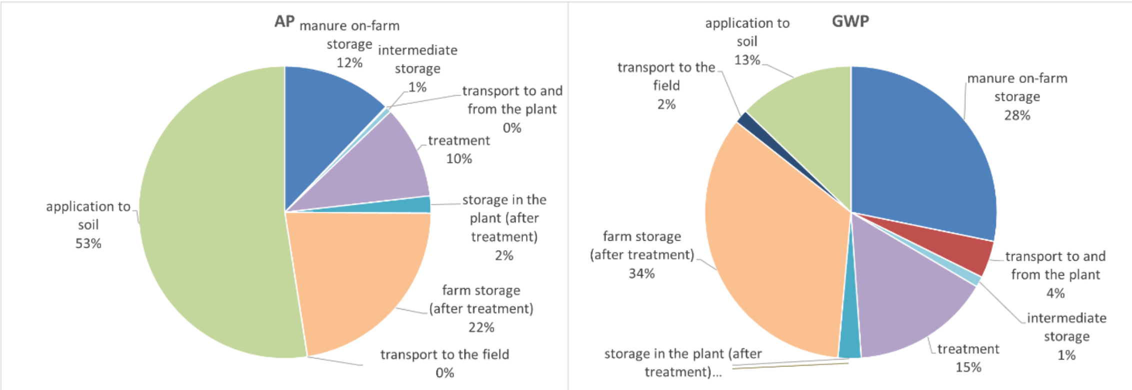

Figure 3. Contribution to acidification potential (AP) and global warming potential (GWP) from different stages of manure management in the collective treatment (CS) scenario (manure is transported from each farm to a collective treatment system and treated effluent is transported back to the farms). The GWP shares have been calculated without considering the emissions offset of the energy produced.

3.3 Comparison of scenarios

Figure 4 shows the differences in AP comparing CS to BS for each livestock unit in order to better understand the effect of the collective treatment plant. As expected the variations are mainly influenced by the differences in NH_3 emissions. However, the differences in emissions of NOx and SO_2 are relevant in relative terms. Compared with those from the BS, NO_x emissions from the CS are 38% lower. This reduction derives from an increase of the emissions during transport (+ 455 kg year^{-1}) and a reduction of emissions during land application (-7960 kg year^{-1}) due to the reduced nitrogen content in the manure after treatment. On the contrary, SO_2 emissions increase significantly (+425%) in the CS due to the transport of manure to and from the treatment plant. Although relevant in terms of variation of emissions, NOx and SO_2 emissions have little influence on the overall result, where the variation of NH_3 emissions (-43%) is predominant in the AP value.

The average reduction of AP achieved by the CS was 43% ± 1.8%, which was mainly due to the reduced emissions during manure storage and field application. The effect of the CS on ammonia emissions does not vary significantly among livestock production units. The main differences are between farms that produce mostly liquid manure and those that produce solid manure. In fact, solid manure is mixed with liquid in the treatment plant and, considering the nitrogen removal, the emissions are reduced.

The emissions of GHGs are greatly influenced by the collective treatment system (Figure 5). The methane emissions are lowered significantly (45%) due to the recovery of energy in the biogas plant. Of course, the methane emissions in the intermediate storage before the transportation to the treatment plant entails some methane emissions (collection was made weekly in each farm) and the treated effluent has still some methane production potential (the volatile solids were 1.4–1.5% of the total mass of slurry applied to the land). However, the main methane emissions in CS are related to the emissions during farm manure storage, both before and after treatment of the manure.

The additional benefit of the treatment plant in the CS refers to the reduction of CO_2 emissions due to energy production. The overall benefit in term of total CO_2 eq. reduction is 55%, which seems to be a very good achievement. The reduction is relatively uniform for all the farms except for two (n. 4 and n. 12). The explanation of this different behaviour is related to the livestock type of these farms (i.e., laying hens that produce solid manure with high nitrogen content). When used in the treatment plant, this type of manure affects N_2O emissions, especially in the nitrification-denitrification process, and these are just partially compensated by the reduction obtained in the field application of treated manure.

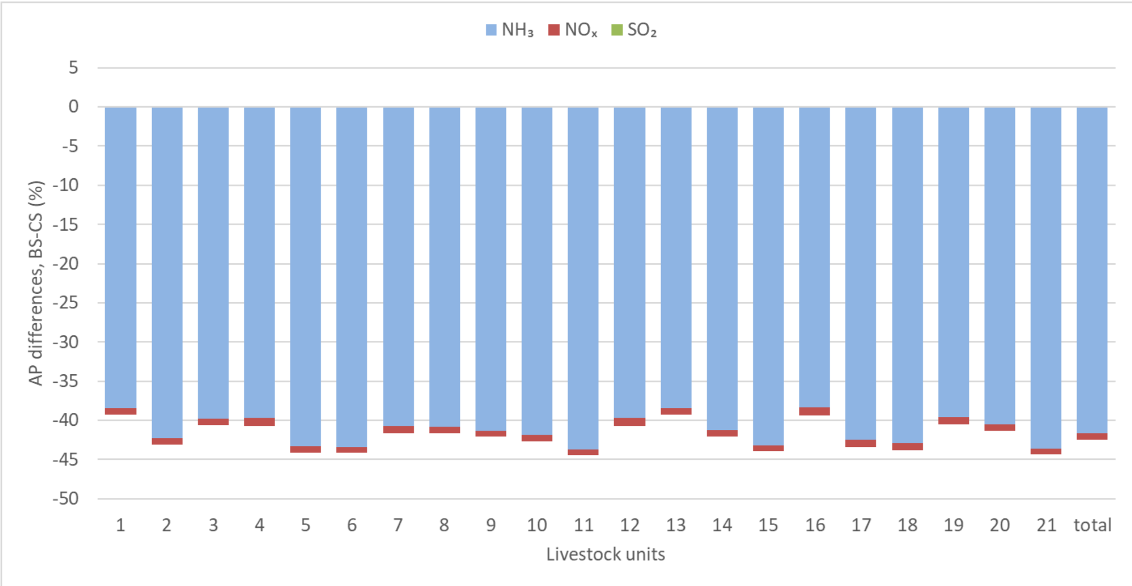

Figure 4. Comparison of acidification potentials for each livestock production unit for the two management systems. CS = collective treatment scenario; BS = baseline scenario without collective manure treatment.

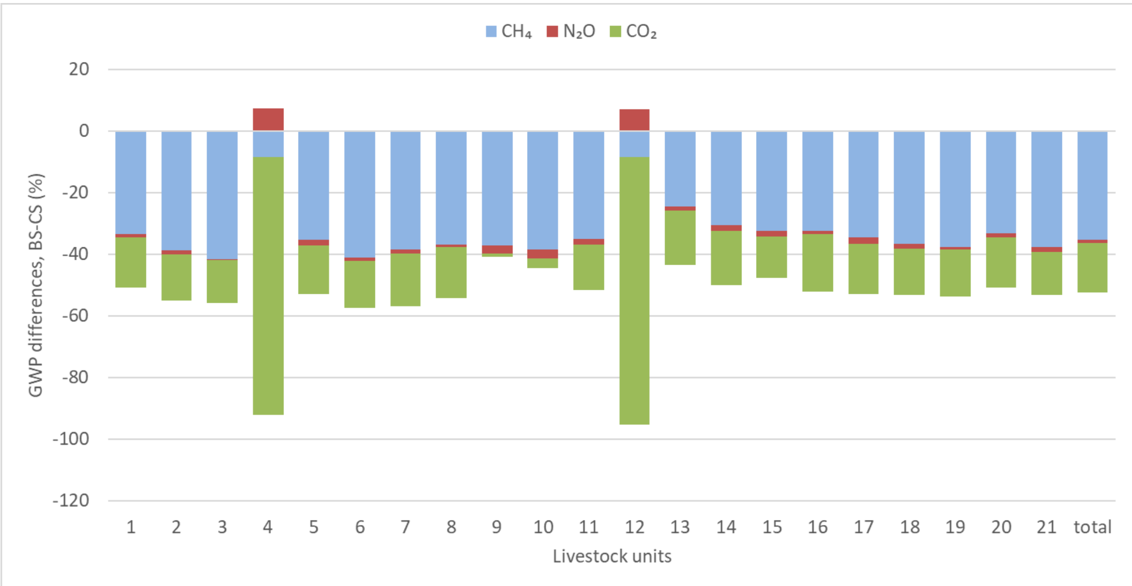

Figure 5. Comparison of GWP for each livestock production unit for the two management systems. CS = collective treatment scenario; BS = baseline scenario without collective manure treatment.

The reduction of GHGs demonstrates how a collective manure management system can be environmentally sustainable, considering climate change impact, despite the higher emissions due to transportation. Thus, collective manure treatment should be carefully considered as a management option in intensive livestock production areas because it can contribute significantly to the overall emissions reduction. In the case study considered, the CO_2 emissions in the scenario with the collective manure treatment plant were over four times those in the scenario without collective manure treatment because slurry transported to and from the treatment plant is mostly accomplished using trucks and tractors with slurry tankers. However, even without considering the CO_2 "saved" by renewable energy production, the effect of collective manure treatment is positive (albeit lower) due to the general decrease of methane emissions.

The assessment highlighted that the two stages in manure management that might be further improved are on-farm manure storage and the application of manure to soil. In fact, both operations typically use the standard techniques (uncovered storages and broadcast spreading); therefore, significant reductions of AP and GWP can be obtained if Best Available Techniques are adopted.

4. Conclusions

The methodology used in this study was effective for assessing the environmental impact of different manure management systems (one including a collective treatment plant and one without the treatment plant). The case study highlighted how a collective manure treatment system might be effective in the reduction of AP and GWP. The combination of anaerobic digestion and nitrogen removal treatment was demonstrated to be sustainable even if the benefits of renewable energy production are not considered. In a collective manure treatment system, the reduction of emissions related to methane collection can compensate the increase in CO_2 emissions from the transport of manure from the livestock farms to the treatment plant and back. Moreover, the income obtained from selling the electric energy produced might reduce the cost of the nutrient removal treatment, helping to make this solution economically sustainable as well as environmentally sustainable. Further benefits may derive from the reduction of odours and the production of a stabilized effluent that can be used as fertilizer more efficiently, with a possible reduction in the use of mineral fertilizers and the consequent further economic and environmental benefits.

Although the methodology used was shown to be adequate for the assessment, it should be pointed out that some aspects, such as the emissions from the different treatments, will benefit from further studies in order to better consider the possible effect of different technological alternatives on the emissions to air.

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